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Implications of energy storage and climate change for pollution control under the Clean Air Act

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ABSTRACT

Increased renewable energy, climate change impacts, and energy storage will affect power system dynamics and thermal plant behavior and emissions. This research explores the effects of these factors on natural gas plant start cycles and consequent emissions. Energy storage can be deployed to mitigate the emissions from increased power plant starting and stopping. Thus, a multi-pollutant, sector-wide approach to protecting air quality will be most appropriate and effective for managing future power system emissions.

1. Introduction

Three key trends in today's power system will impact regional and national air quality and must be evaluated and addressed. First, there is an evolution from a large centralized to a more distributed power system, as older coal and nuclear power plants are retired and thousands of smaller power plants and distributed generation facilities come online. Second, increasing quantities of variable renewable generation from wind and solar require increased flexibility from the balance of the system. Third, as the climate continues to change, changes in precipitation patterns and timing of snowmelt will change hydroelectric plant availability and operation, requiring increased deployment of other sources of flexibility such as natural gas power plants. All of these changes create operational challenges for the power system operator and can increase both the emissions of air pollution per unit of energy, including greenhouse gases, at the individual power plant level, and the complexity of managing emissions sources. The research associated with this paper modeled these trends in the western United States, and examined the potential for energy storage to mitigate air pollution. This paper focuses on the policy implications of the findings.

In general, power system flexibility is required to follow rapid changes or ramps in net electrical load. Variable renewable generation tends to increase the need for system flexibility, which can be provided by: more nimble thermal power plants, such as natural gas combustion turbines; well-managed demand response mechanisms; and energy storage systems that are able to offset variability by shifting generation and load across time. Each of these options includes tradeoffs, and measuring the best way to provide needed flexibility in a continuously changing electrical landscape poses a challenge to electric utility regulators, just as managing changing patterns of pollutant emissions poses a substantial challenge to air quality regulators.

Air regulators have considerable latitude in developing plans for controlling or reducing pollution. For example, the United States Environmental Protection Agency has advocated a multi-pollutant approach (Clean Air Act Advisory Committee, 2011; United States Environmental Protection Agency, 2008), and has also encouraged agencies and permittees to explore non-traditional control technologies including outside-the-fence measures such as energy efficiency and renewable energy. A flexible regulatory approach may be particularly desirable in today's power sector due to the interconnected characteristic that allows one facility to affect another's operational dynamics and consequently its pollutant emissions.

This may be especially the case in areas where hydroelectric power operations and availability are expected to alter with climate change, such as the desert Southwest in the U.S. Changes in precipitation and snow patterns are predicted to cause seasons of extreme drought in the desert Southwest, as well as earlier and greater runoff in the northwest and mountain regions (Lynn, 2015). This will cause changes in the availability of hydroelectric facilities, which are currently a large source of flexibility on the electrical power system. In the past two

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years, California has experienced both reduced hydroelectric availability due to drought, and situations in which hydroelectric plants must run continuously in order to avoid flooding (Gleick, 2016). These changes create additional demands for flexibility in the power system.

When thermal power plants spend more time ramping up and down, stopping and starting, running in spinning-only mode or operating at lower output levels, there is an increase in average air pollution emissions per MWh due to the time spent at these suboptimal operational states (Ivanova et al., 2017; Kumar et al., 2013). Because of legal limits on air pollution emitted from individual power plants, and because reducing greenhouse gases and other pollution is a primary goal of introducing additional variable wind and solar generation, these increases in emissions rates must be mitigated. The tools for reducing emissions rates can be some of the same that provide power system flexibility, mentioned above, by smoothing out electricity load and generation profiles and allowing fossil fuel plants to operate at more optimal levels. System-wide modeling can help air regulators and electricity producers identify emerging air quality issues and evaluate potential solutions that cannot be addressed by studying single power plants or utility balancing areas.

Energy storage offers multiple values to the power system, including potential use as pollution control technology (Behles, 2015). Nevertheless, energy storage is inherently challenged in how it can and should be compensated financially for all of the various benefits it provides to the power system (Kintner-Meyer, 2014; Sioshansi et al., 2012). Energy storage is both infrastructure and a source of generation (Bhatnagar and Loose, 2012; Wasowicz et al., 2012); and no market adequately compensates all of the services it provides (Johnson et al., 2013; Mullendore, 2015). As a potential pollution control mechanism, storage may have yet another value that is not routinely evaluated or compensated.

While energy markets continue to evolve and adapt to storage, air regulators should work with energy regulators to explore storage's potential for reducing power sector emissions. Air regulators and power plant owners will increasingly be challenged to achieve power plant emissions goals, particularly for the most nimble thermal power plants, under changing electricity grid conditions. This is especially relevant for locally important pollutants in areas that are already non-compliant with air quality standards. Consideration of storage's potential pollution control benefits therefore adds new and very useful dimensions to the discussion of storage's value. These benefits are additional to those improving system reliability and efficiency.

The research results provided in this paper examine the Western U.S., with a focus on the desert Southwest. It tests changes in the coal, renewable, and hydroelectric generation fleets in order to explore energy storage's potential for emissions reduction. While there are a number of tools for managing changes in power system dynamics, such as transmission expansion, demand response, and energy efficiency, storage is the most readily deployable and controllable, and can be co-located with new power plants in order to directly quantify its utility for pollution control. Thus, this work focuses on storage's contribution and what policy changes, if any, should be considered in order to facilitate this contribution.

1.1. Pollution control background

1.1.1. Pollution control overview

Two kinds of power plants are most commonly used for new thermoelectric generating capacity: natural gas combustion turbines (CT) and natural gas combined cycle (CC) plants. Both types of plants emit a number of regulated air pollutants, primarily oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), and volatile organic compounds (VOCs). Each of these has specific factors that influence its magnitude, including the stage of plant operation, the conditions of fuel combustion, and pollution control technology deployment. Pollution control technologies are typically designed to address individual pollutants by modifying the combustion conditions or by filtering the byproducts of combustion. It is worth noting that NO_x, CO and VOC emissions are all significantly higher per unit of fuel when combusted in gas turbines operating at lower load levels or at variable load levels (United States Environmental Protection Agency, 2000), and that none of the common control technologies is effective during startup and shutdown (State of Georgia Department of Natural Resources, 2010). Additionally, some of these control technologies interfere with others (United States Environmental Protection Agency, 2000).

Because of the way control technologies operate, and because of the way that plant operation is expected to change in a changing grid, energy storage deployment may serve as a significant pollution control option to reduce stops, starts, and "spinning states" in addition to the customary control technologies, not in place of them.

1.1.2. Potential for storage in emissions reduction

By virtue of its ability to move energy across time and make more efficient use of the existing generation fleet, storage can reduce plant stops and starts or the need for plant idling for spinning reserves (Southern California Edison, 2017). By reducing the time that gas plants spend in these operating states, storage can reduce the emissions rates of multiple pollutants at these power plants.

1.1.3. The Clean Air Act and the power sector

Much of the federal Clean Air Act (CAA) protects and improves air quality in the United States through a series of air quality and emissions standards (United States Environmental Protection Agency, 2007). The requirements that limit emissions from stationary sources in an area are typically met through individual limits on each existing and new source of pollution; these limits in turn are met using various on-site and off-site technological solutions, the level of which is dictated by the specific pollutant and the existing air quality where the source of pollution is located (United States Environmental Protection Agency, 2013). In some cases, limits can be met by reducing pollution across an entire class of sources (such as power plants), across different types of sources that emit the same pollutant, or through offsets from reductions by other polluters in the same area (United States Environmental Protection Agency, 2012). States must develop and execute implementation plans (SIPs) that demonstrate how they achieve and maintain levels of pollution below air quality standards (United States Environmental Protection Agency, 2013). Further, the EPA in 2015 updated regulations to ensure that state plans include adequate control of emissions during startup, shutdown, and malfunction events (United States Environmental Protection Agency, 2015a).

For existing or new power plants, technology controls to meet pollution reduction goals are evaluated on the basis of their comparative technical merit in other installations and their economics (United States Environmental Protection Agency, 2013). Specifically for reducing carbon dioxide (CO_2), options that offer the same services (electricity production) through lower-emitting sources, such as energy efficiency, renewable energy, and potentially storage, are encouraged by the EPA (Lashof et al., 2014, 2013; U.S. Environmental Protection Agency Office of Air and Radiation, 2015; United States Environmental Protection Agency, 2012). Under the Clean Power Plan, which was proposed by the federal government in order to limit CO_2 emissions from the power sector, states were given considerable latitude to reduce emissions through measures "outside the fence" of individual power plants (United States Environmental Protection Agency, 2015b). Generally, the EPA advocates for flexibility in circumstances in which it can be demonstrated that there are other more cost-effective means for reducing emissions than a strict post-combustion control technology (United States Environmental Protection Agency, 2012). This flexibility is allowed as long as the strategy results in quantifiable, permanent, enforceable reductions and is as effective or more effective than traditional measures onsite.

1.1.4. Support for a multi-pollutant approach

While the historic approach of the Clean Air Act and the EPA largely has been to regulate each pollutant individually at each facility, there are strategies that would support very cost-effective multiple pollutant reductions; many parties have recognized and recommended a multi-pollutant approach to emissions control and air quality management (James and Colburn, 2013). In 2004, the National Research Council recommended that the EPA consider a multi-pollutant air quality management plan (National Academy of Sciences, 2004), calling for integration of current assessment, planning, and implementation efforts across all air quality and environmental issues. Building upon the 2004 research, the EPA's Office of Air Quality Planning and Standards began a transition toward a multi-pollutant treatment of regulations. In 2008, the EPA released a report (United States Environmental Protection Agency, 2008) calling for an integration and optimization of air quality management strategies. It also explained the technical underpinnings of a multi-pollutant approach, providing specific examples, and showcased the development of initial modeling and analytical tools available to state regulators.

In 2011, the EPA's Clean Air Act Advisory Committee provided a framework (Clean Air Act Advisory Committee, 2011) to the EPA for a multi-pollutant reduction strategy in major US industry sectors to align the major air quality programs and coordinate their timing and obligations. The Committee argued that an incremental, sector-based multi-pollutant approach was already underway and should continue, in order to achieve equal or better pollution control results at lower costs. This sector-based approach could yield a simpler regulatory system, reducing redundancies and making it easier for sources to comply with multiple requirements.

1.1.5. Innovative pollution controls

Because many approaches that would yield emissions reduction benefits for multiple pollutants are not direct "end of pipe" measures, an intrinsically related topic is the EPA's approach to "outside-the-fence" options for pollution control, or the consideration of measures that are alternatives to the typical on-site chemical or physical equipment pollution reduction strategy. One historical example of an EPA-supported "outside-the-fence" measure is the cap-and-trade program that was successfully implemented to reduce sulfur dioxide emissions from power plants.

In 2004 and 2005, EPA published a series of guiding documents (United States Environmental Protection Agency, 2005, United States Environmental Protection Agency, 2004a,b) to help air regulators incorporate energy efficiency, renewable energy, and other voluntary or emerging measures from the electric sector into air pollution reduction implementation plans. EPA's 2012 Roadmap for incorporating renewable energy and efficiency measures into state plans strongly encouraged air regulators to collaborate with state energy offices and public utility commissions to coordinate regulation, monitoring, and sharing of information and tools (United States Environmental Protection Agency, 2012).

1.1.6. A proposed multi-pollutant, outside-the-fence controls approach

The Regulatory Assistance Project (RAP) "E-Merge" initiative for integrated multi-pollutant control contemplates a future air quality regulatory environment in which state agencies optimize their approach to emissions reduction across pollutants. They accomplish this by developing emissions targets across multiple pollutants, identifying multiple potential technological approaches to emissions reduction, and quantifying the potential for each technology to reduce emissions for multiple pollutants under a variety of operating conditions. This approach would benefit air regulators in that it offers economic and technology efficiency in mitigating emissions across pollutants, and helps to anticipate and avoid the problem of technological solutions for individual pollutants that counteract or impede each others' effectiveness. This approach could also offer cost savings to source operators such as electric utilities that have to reduce pollution from power plants, by allowing and permitting technology solutions for achieving multiple air quality goals simultaneously.

This methodology would involve alteration of the customary legal approach to pollution control. It might also necessitate an advance in technical capacity and collaboration among the permittee and regulator in order to have available the requisite tools for evaluating and comparing pollution reduction options. This research takes a step toward informing the development of this approach by assessing the potential for one option, energy storage, to mitigate emissions across pollutants, through the use of quantitative data and calculations based on power plant modeling and air quality permits.

1.2. Literature

Established multi-objective optimization techniques have been used for analyzing multi-pollutant programs in Europe and Asia (Chestnut et al., 2006; Ciucci et al., 2016; Zhang et al., 2015). This work largely concludes that better (air quality) results are achieved at lower cost when policies are streamlined across pollutants. Other research, focused specifically on multiple air pollution regulations and climate change goals, determined that further emissions reductions could be achieved across pollution and climate change programs at lower cost (Bollen et al., 2010, 2009; Dong et al., 2015; Rive, 2010; Zeng et al., 2017).

An evaluation (Forte et al., 2002) of nine multi-pollutant control technologies concluded that some technologies are quite effective at controlling multiple pollutants and more practical and efficient than distinct control technologies. An assessment (Konschnik and Peskoe, 2014) of states' ability to implement the Clean Power Plan recommended harnessing existing utility planning processes such as integrated resource planning and expanding the process to create an enforceable scenario-driven air quality management approach. Similarly, an analysis of regional governance structures for integrating energy and climate law (Wiseman and Osofsky, 2015) suggested that multi-state, collaborative efforts could be more effective than individual pollutant controls and patchwork efforts from state to state. An exploration of the implications of CO_2 emissions regulations for the power sector (Perlis, 2014) concluded that outside-the-fence measures were critical to emissions control.

Behles (Behles, 2015) examined the legal and technical framework for using electricity storage devices as Best Available Control Technology (BACT) for new power plants, as defined and required under the Clean Air Act. Behles asserted that BACT's broad definition should enable regulators to consider energy storage or storage-and-renewables to serve as BACT for electricity generation facilities, demonstrating through her analysis of case law and the original Clean Air Act that the statutory and regulatory language would support such a broader reading of the CAA and application of BACT.

An important aspect of much of the power system modeling research on storage deployment (de Boer et al., 2014; Denholm et al., 2013; Edmunds et al., 2015; Koritarov et al., 2013; O'Dwyer and Flynn, 2015) is the fact that the increased deployment of variable renewable energy sources causes thermal plants on power systems to run in transient states more often (stopping and starting more frequently), which increases emissions from those plants (Ivanova et al., 2017). Investigating the impacts of deployment of storage on these plants' operation at transient states can inform decisions about storage's merits as a pollution control device.

2. Theory

2.1. Air pollution permit review

Power plant air pollution permits and technical supporting documents for the construction and/or operation of 26 CT and 26 CC

facilities were analyzed. The allowable emissions for power plant starts and stops were calculated and presented as a multiplier of the allowable emissions for normal power plant operations. This ratio represents the total amount of pollution allowed during one cycle of shutdown and startup divided by the total amount of pollution allowed during an equivalent amount of time of normal operation under ideal circumstances (full load). Details of the methodology for these calculations are presented in the associated work (Wadsack, 2018).

2.2. Production cost modeling and the TEPPC Dataset

The PLEXOS production cost model (PCM) from Energy Exemplar[1] was used to evaluate a set of scenarios of energy storage, renewable energy, and hydro-electricity generation deployment, in terms of system operating costs, reliability parameters, and CO_2 emissions. The PLEXOS model was used with the Western Electricity Coordinating Council (WECC) Transmission Expansion Planning Policy Committee (TEPPC) 2024 Common Case dataset, which represents the expected WECC bulk power system in the year 2024.

2.3. Selection of cases

This study used the 2024 TEPPC dataset as a starting point, and reduced the natural gas fuel price and shut down a set of coal-fired power plants in the Southwest as a reasonable reference case. Two central test cases included high levels of regional (Arizona and California) renewables and, further, the extreme reduction of regional hydroelectric availability on the Colorado River system and in California. To each of these test cases, different configurations of 100 MW battery storage units were added to the system in order to test the effects of modest utility-scale west-wide deployment. The various storage scenarios represent differences in geographic configuration and energy capacity. In this work, a subset of all of these test cases was used (Table 1). The reference case is called TEPPC + . The AZ30 case includes 30% renewables in Arizona and 40% renewables in California. The AZXD case includes reduced hydroelectric capacity in Arizona and California, and the WECCST2XD case includes all of these components, with the introduction of 100 MW of 2-hour energy storage in each electricity balancing area (BA) in the West.

2.4. Case study: Application of modeling results to air pollution permit compliance

The results of the power system modeling were analyzed in order to develop a characterization of the total annual percentage increase or decrease in power plant starts, by power plant type, for the plants across the Arizona and California BAs (where the bulk of system changes were being tested). The comparison of the central test case (AZ30) to the reference case (TEPPC+) shows the effect of adding renewable capacity. The comparison of the drought case (AZXD) to the central test case shows the effect of drought. The comparison of the storage case (WECCST2XD) to the drought or central test case indicate the effects of the storage deployment scenario.

These results were then applied to one case of an individual power plant's air quality emissions permit as an example to illustrate the potential effect of future power system scenarios on air pollution emissions and permit compliance. These comparisons used the average regional changes of power plant starts and stops, applied to the details of one specific power plant, in order to present a concrete example for illustrating the policy argument posed in this research

[1] See https://energyexemplar.com/software/plexos-desktop-edition/.

Table 1
Select cases modeled and analyzed.

Abbrev.	TEPPC+	AZ30
Case details	Reference 2024	Central test case

Abbrev.	AZXD	WECCST2XD
Case details	AZ30 plus drought	2-hr storage in all BAs plus drought

3. Results

3.1. Air permit review

Recent air permits granted for the construction of CC and CT natural gas plants provide insights into the limits of control technologies and the magnitude of emissions expected and allowed during different plant operating conditions. In addition to limiting emissions rates during normal plant operation, each of the permits provides the plant owner with additional guidelines for controlling emissions during startup and shutdown.

The permit analysis showed that the rate of emissions allowed during plant startups and shutdown was as much as 1400% of normal CT operating emissions for NO_x (See row 5 of Table 2). Generally, the existence of annual total emissions caps and rolling-average emissions limits will restrict the total number of starts/stops that can take place during any month or year.

3.2. Production cost modeling of plant stops and starts

The number of total annual starts (stop/start cycles) for each fossil-fueled thermal plant type in the Arizona and California BAs varied significantly across the modeled cases (Fig. 1).

Extreme drought increases the utilization, and consequently the need for starts, of all thermal plants and CT plants in particular. The effect of increased renewable energy was to increase CT plant starts by about 6%, and extreme drought increased starts by more than 30% on top of this. Storage deployed west-wide reduces the number of power plant starts dramatically (by more than 20%), indicating that storage is providing significant system flexibility and also reducing the cost and emissions associated with repeated CT plant starts.

3.3. Applying model results to plant permit cases

This case study focuses on a recently built Arizona CT power plant, composed of five 102-MW units, which was built with the expectation of providing flexibility for a power system with an increasing amount of solar generating capacity, with each unit expected to have up to 730 cycles of shutdown/startup per year (Maricopa County Air Quality Department, 2016).

When drought, compounded with increased renewable energy on the Southwestern electrical system, dramatically increases the number of power plant starts, the consequence for maintaining air quality permit compliance is to significantly reduce the total number of plant operating hours (Table 3).

For a CT unit in this case study anticipating 365 starts per year under reference case circumstances, the percentage increase in starts expected due to drought and renewables combined (39.5%) would reduce total maximum annual potential operating hours by 10.3% (see column 3 of Table 3). If the plant were operating with 600 starts per year, the start increases from drought would reduce allowed operating hours by more than 20%.

The introduction of storage mitigates drought's effects on plant starts considerably, thus restoring part of the power plant's ability to operate for more hours while still complying with its NO_x emissions permit limits (see column 5 of Table 3). Applying the modeling results

Table 2
Air pollution allowed by plant type during power plant starts/stops and normal operations.

Plant type	Pollutant	Mean normal operations lbs. pollution/MWh	Range: Multiplier of normal operating emissions allowed at startup	Range: Multiplier of normal operating emissions allowed during shutdown
CC	NOx	.064	3.9 to 39.2	1.6 to 14.8
CC	CO	.048	15.7 to 479	15.7 to 479
CC	VOCs	.027	2.52 to 231	9.3 to 231
CT	NOx	.196	2.1 to 10.1	0.58 to 14.2
CT	CO	.154	2.7 to 28.4	0.57 to 34.9
CT	VOCs	.033	2 to 29.0	2.7 to 34.3

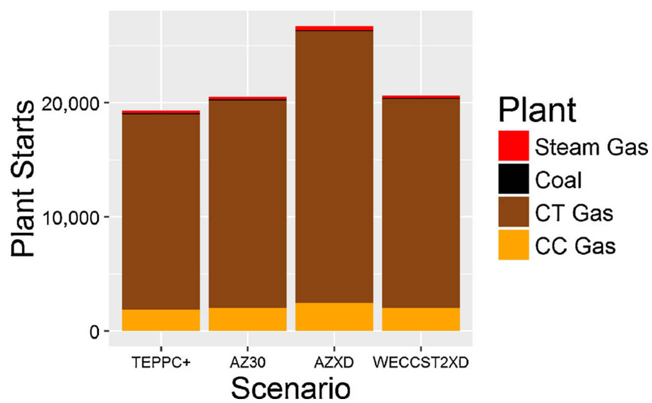

Fig. 1. Total annual power plant starts, by type, summed for all plants in the AZ and CA BAs.

to this hypothetical example, even in the case of the CT plant being started 800 times per year in the reference scenario, the introduction of storage enables the plant to return to almost 94% of its original expected operating hours.

The results of this work serve to illustrate important interactions in the power system and the effects that energy storage deployment can have in mitigating expected future challenges to maintaining air quality.

4. Discussion

The results presented here show that utility-scale energy storage offers significant system flexibility and air quality benefits. The modeling work focused primarily on storage's impact on emissions and plant starts. Storage's effect on reducing CT and CC plant starts makes a significant contribution to pollution reduction. The increase in plant starts due to the addition of renewables, but especially due to the possible future extreme drought circumstances, show that CC and CT power plants would have to allocate a significant portion of their annual NO_x, CO, and VOC emissions caps to starting and stopping in place of electricity generation. This means that they would have to reduce the number of operating hours, which is their source of revenue, in order to maintain compliance with pollutant limits, because of the increase in stop and start cycles, which are providing flexibility to the power system as a whole. This paper does not directly consider the implications of the modeling results and air quality permit analysis for CC plants. Because CC plants typically spend more time running than do CT plants, it is possible that for some plants, the results shown here would in fact have an even more immediate or likely negative impact on CC plant operations than in the illustrated CT plant example.

Objectives of this research were to explore the implications of modeling results from a series of scenarios of the desert Southwest future power systems for air quality decision-making processes. The way that air pollution targets are met is evolving; the way that individual permits are issued needs to evolve with this process change. These analyses demonstrated that storage is a viable option for reducing start-and-stop-related pollution under specific sets of expected future conditions. This suggests two things: first, that it would be helpful to model a wider range of likely future circumstances in predicting the air pollution emissions associated with permitted facilities; and second, that air quality regulation mechanisms for rewarding technologies like storage for providing specific pollution-reduction services should be explored. These mechanisms, however, should reward any technologies or approaches that can cost-effectively provide these solutions, in order to enable entrepreneurship and technology development and foster true economic efficiency in pollution control. This suggests that sector-wide modeling and routine investigation of multi-pollutant control measures should be standard practices in air quality regulation.

As shown here, modeling potential future scenarios for power plants and the impact on their various operational conditions and emissions can be a powerful tool for developing a reasonable pollution control permit and for evaluating the effectiveness of different control strategies. Because of the interconnected nature of the power system, this suggests that air regulators would benefit not only from access to modeling capacity, but also from greater leeway to implement a multi-pollutant approach incorporating outside-the-fence measures, in order to streamline pollution control across this industry sector. Through this approach, likely informed by collaboration with state energy offices, utility regulatory commissions, and electric utilities themselves, air regulators could achieve greater protection and improvement of air quality under a variety of potential future circumstances in the most efficient manner.

5. Conclusion

As renewable energy advances, aging baseload power plants retire from the electrical system. Coal, inefficient natural gas, and nuclear plants are curtailed due to cost; climate change conditions, such as the reduced availability of water, affect the operation of the hydroelectric generation fleet. In order to continue protecting public health and air quality in an economically efficient manner, the effective achievement and maintenance of air quality standards must strike a balance between individual plant local impacts and accountability for other impacts on the system, between individual plant and sector-wide limits and measures. Federal guidance should encourage and direct the use of multi-pollutant and outside-the-fence pollution control options for the power sector.

This research explored the operational impacts of deploying large-scale energy storage across the Western Interconnect. As renewable penetration increases nationwide, this will reduce the emissions associated with the energy used to charge storage units. Storage deployment will mitigate the negative emissions, operational, and wear-and-tear effects on the thermal fleet that is currently being deployed to balance variable generation. Thus, evaluating opportunities like using storage as a multi-pollutant control technology should absolutely be considered as an air quality regulatory strategy as the power sector evolves.

The increased emissions due to plant spinning, stops and starts as a result of increased variable generation and decreased hydroelectric capacity could be mitigated in many ways. Because energy storage is technically deployable now, is under the immediate control of utilities,

and can be precisely monitored and operated, it provides a concrete mechanism for supplying system flexibility while reducing emissions from plant stops, starts, and spinning. An important ancillary conclusion to draw from this work is related to hydropower flexibility. Results showed that a loss of some flexible hydropower due to severe drought in the Southwest led to a dramatic increase in CT and CC starts and stops. Thus, the storage inherent in Colorado River and California hydropower already provides a significant benefit in terms of electrical system emissions.

This research advanced current knowledge regarding electricity storage's potential as an emissions control tool, and provided an example of one modeling methodology for evaluating cross-sectoral emissions control options. The results support the argument for a sector-wide, multi-pollutant approach to emissions reduction, and suggest that air regulators should collaborate with state regulatory commissions, energy offices, and electric utilities to integrate and streamline pollution control options with the resource planning process.

Table 3
Operational effect of NO_x emissions limit on CT plant in AZ due to increased starts from integration of renewables and extreme drought.

Assumed annual stops/ starts	Stops/ starts with drought + RE increase (AZXD case)	Reduction in allowed operating hours due to stop/ start increase	Number of starts with addition of west-wide 2-hr storage (WECCST2XD)	Resulting percent of original operating hours allowed with storage mitigating stop/start cycles
365	509	10.3%	392	98.1%
600	837	20.5%	645	96.2%
800	1116	33.0%	859	93.8%

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